Experimental Study of Pressure Influence on Tunnel Transport into 2DEG

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We present the concept and the results of pilot measurements of tunneling in a system Al/δ_{Si}-GaAs under pressure up to $2\,GPa$ at $4.2\,K$. The obtained results may indicate the following: the barrier height for Al/δ-GaAs equals to $0.86\,eV$ at $P = 0$ and its pressure coefficient is $3\,meV/kbar$; charged impurity density in the delta-layer starts to drop from $4.5 \times 10^{12}\,cm^{-2}$ down to $3.8 \times 10^{12} cm^{-2}$ at about $1.5\,GPa$; metal-insulator transition may occur in 2DEG at about $2\,GPa$.

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I. INTRODUCTION

In the very vicinity of metal-insulator transition charge transport properties of a 2DEG depend not only on the interplay between the electron density and disorder but also on the influence of quasi-particle interaction. Tunneling measurements under pressure may provide a useful experimental approach to this fundamental problem by the following reasons. Contrary to magnetotransport measurements that obviously deal with the carriers only in filled subbands of spatial quantization, tunneling allows also to get an information on energy spectra of empty higher lying subbands. Many-particle effects (exchange and/or electron-phonon interactions) manifest themselves in tunnel characteristics either through the changes in a barrier shape [1] or as self-energy effects [2]. Examples are the specific singularities at biases near ($36.5\,mV$, corresponding to LO phonons in GaAs and the so called zero bias anomaly originated from the interaction between the electrons revealing as a peak of tunnel resistance [1, 3]). High pressure may be used as a tool that allows to change substantially the electron density as well as the energy levels in a quantum well formed by selective doping of a narrow layer near the Me/GaAs interface, maintaining concentration and distribution of static scattering centers (impurities, dislocations etc) practically constant. An additional mechanism of the pressure influence on the charged impurity density may be related to the existence of DX centers as it was shown earlier in magnetotransport measurements [4]. In this paper we present a first attempt (to our knowledge) to measure normal tunneling in a system Al/δ_{Si}-GaAs with 2DEG formed by the delta-doped layer close to the interface under pressure up to $2\,GPa$ at $4.2\,K$.

II. EXPERIMENTAL

The tunnel structures, shown in FIG. 1, were fabricated in IRE RAS following the procedure described in [3]. On (100) GaAs substrate by the MBE method an undoped buffer layer ($p \sim 5 \times 10^{15}\,cm^{-3}$) was grown. The delta-doped layer with width about $3\,nm$ at the depth of $20\,nm$ from Al/GaAs interface containing $5.2 \times 10^{12}\,cm^{-2}$ Si atoms was formed at $570\,°C$. At the final stage of growth cycle, an Al film of $80 - 100\,nm$ width was deposited from the Knudsen cell in the same MBE chamber. Photolithographically shaped tunnel junctions were supplied with Au-Ge-Ni alloy ohmic contacts to the delta-layer.

In this structure only one level is initially occupied at $T = 4.2\,K$. The energy diagram of the sample that defines tunneling current in the direction normal to the interface is shown on FIG. III. The spatial distribution of the electric potential that forms both the tunnel barrier and the quantum well depends on the surface barrier height, on doping level in delta-plane and on volume acceptor density in the epitaxial layer. A system of energy levels exists in the quantum well that gives rise to the dips on tunneling spectra corresponding to the stepwise changes in conductance versus applied bias. One should note that the 2D levels are changed in the biased diode as the barrier (and QW) shape selfconsistently depends on the charge density in the delta-layer. FIG. III shows the variation of the 2D levels

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in the well with the applied bias, calculated for $p = 1.5\,GPa$ by simultaneous solution of Poisson and Schrödinger (in Hartree approximation) equations.

The pressure was generated at room temperature in a stand-alone high-pressure cell of a piston-cylinder type filled with 40% transformer oil and 60% pentane mixture as a pressure transmitting medium [5]. After slow cooling down to low temperatures the $I(V)$ curves were measured within the accuracy $7\frac{1}{2}$ digit DC voltmeter. The actual pressure was evaluated by the change of the critical temperature T_c of Sn wire placed *in situ* using the expression: $\Delta T_c = -0.495P + 0.039P^2$ (the pressure P in GPa) [6].

Under pressure the tunnel resistance tends to increase rapidly with pressure [7]. This made us to confess that the usual measurement procedure based on modulation technique is not well suited for the case of large tunnel resistances. Instead, we used direct current $I(V)$ measurements and subsequent numerical derivation to reveal the fine features due to the subband structure and many-particle effects. The comparison of the both measurement techniques for the case of zero pressure when the tunnel resistance is of moderate value, confirms the validity of DC implementation, that becomes even more effective under pressure when the resistance grows by several orders of magnitude (FIG. 3). Results of $I(V)$ measurements in terms of differential tunneling conductance as well as its logarithmic derivative, *i.e.* tunneling spectra, are presented in FIG. 4.

III. ANALYSIS

Model calculations were used to evaluate the tunneling barrier shape and the position of energy levels in the QW, and hence the tunneling spectra and the value of tunnel resistance at zero bias $R_0(P)$, the latter being a simple and convenient scalar quantity to compare the model assumptions with reality.

From our previous studies of Shottky barrier Me/n^+-GaAs [7] we knew that barrier height at the Al/GaAs interface may change with pressure not the same way as the energy gap in the semiconductor does. Possible presence of DX-centers could also change effective charge state of the impurity in the delta-layer under pressure. Thus we considered such an ambigous at high pressure quantities as free parameters and tried possibly fit the calculated and measured spectra and zero bias resistances at different pressures.

We found that the best fit to the experimental spectra at pressures up to $1.5\,GPa$ may be attained if one assumes that the barrier height grows at the rate of $3\,meV/kbar$, that is considerably lower than the pressure coefficient of the band gap $10.8\,meV/kbar$ [8].

Comparison of the zero bias resistances (FIG. 5) shows that while a reasonable agreement with the experiment (filled circles) may be achieved for $1\,GPa$ with the charged impurity density in delta-layer $4.5 \times 10^{12}\,cm^{-2}$ (same as at $P = 0$), a systematic underestimate of the calculated resistance is observed at $P = 1.5\,GPa$. A better fit for that pressure (open circle), that gives also closer fit of tunnel spectrum, may be obtained if one assumes the decrease of charged impurity density in delta-layer down to $3.8 \times 10^{12}\,cm^{-2}$ at $1.5\,GPa$.

A possible reason for that may be related to the electron capture by DX-centers, making them either negative [9] or neutral [10], that changes the effective charged impurity density in the delta-layer. To become resonant with the ground state at $1\,GPa$, DX-level at $P = 0$ should be about $170\,meV$ above the conduction band edge that is not quite consistent with the previous data [11], obtained from magnetotransport measurements in a deep lying delta-layer with multiple occupied 2D-levels.

We could not obtain any reasonable model description of our experimental data at $2\,GPa$. The estimation allows supposing that these measurements correspond to the state when a metal-insulator transition occurs and the ground level is depleted, but this cannot explain the existence of slight remnants of higher levels in spectrum at negative biases.

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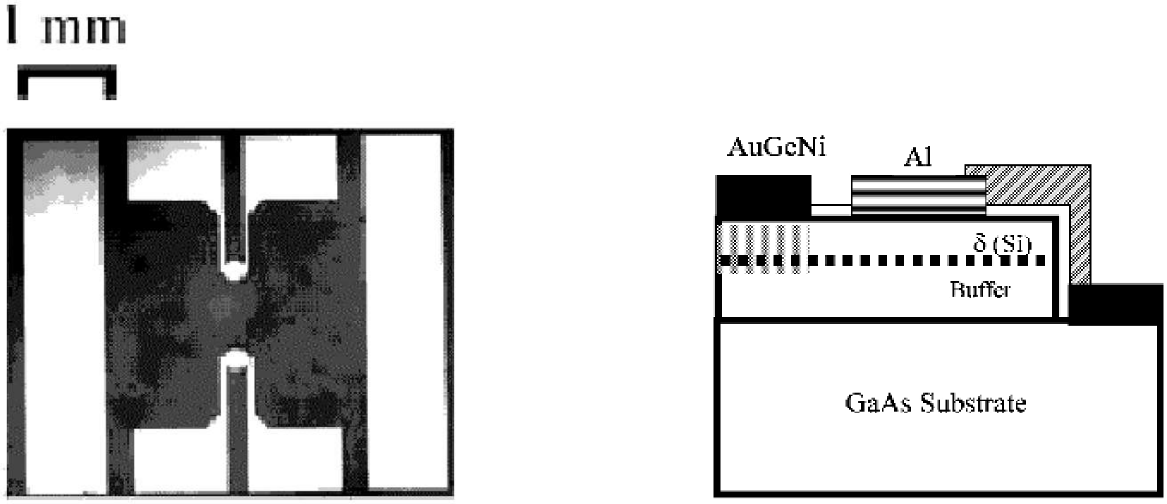

(a)

FIG. 1: Plain view (a) and schematic cross-section (b) of the sample Z1B8.

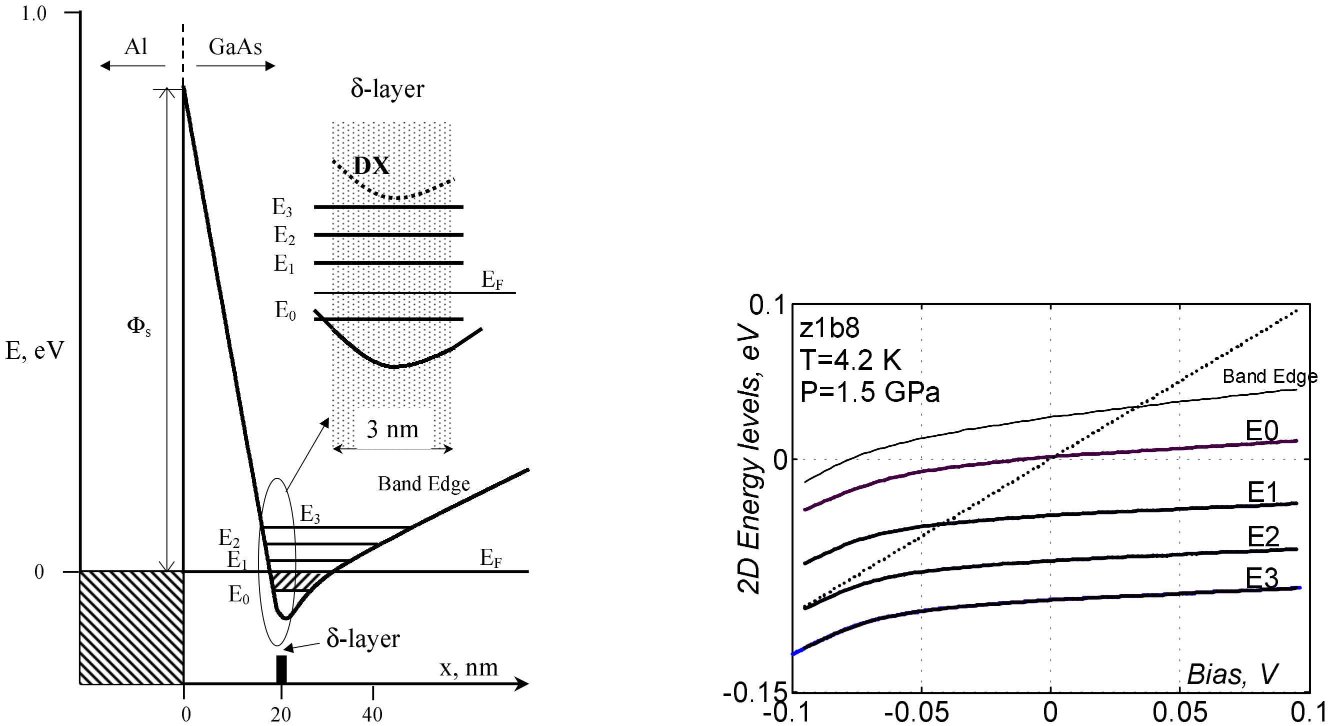

FIG. 2: (a) Energy diagram in the vicinity of Al/GaAs interface. Dotted line represents possible position of DX-level. (b) The calculated energy of the 2D-levels relative to Fermi energy of the metal electrode at $P = 1.5\,GPa$. The corresponding features on the tunneling spectrum may be found graphically as the points of intersection between the levels and the dotted line.

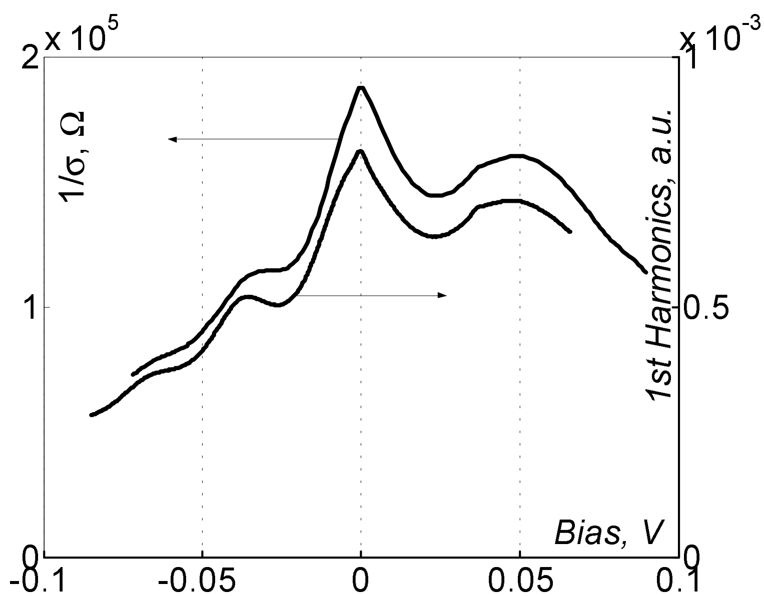

FIG. 3: Comparison of DC and modulation techniques. The upper curve is the result of numerical derivative of DC $I(V)$, the lower one is a signal of the 1st harmonics in usual modulation technique for the same sample at zero pressure.

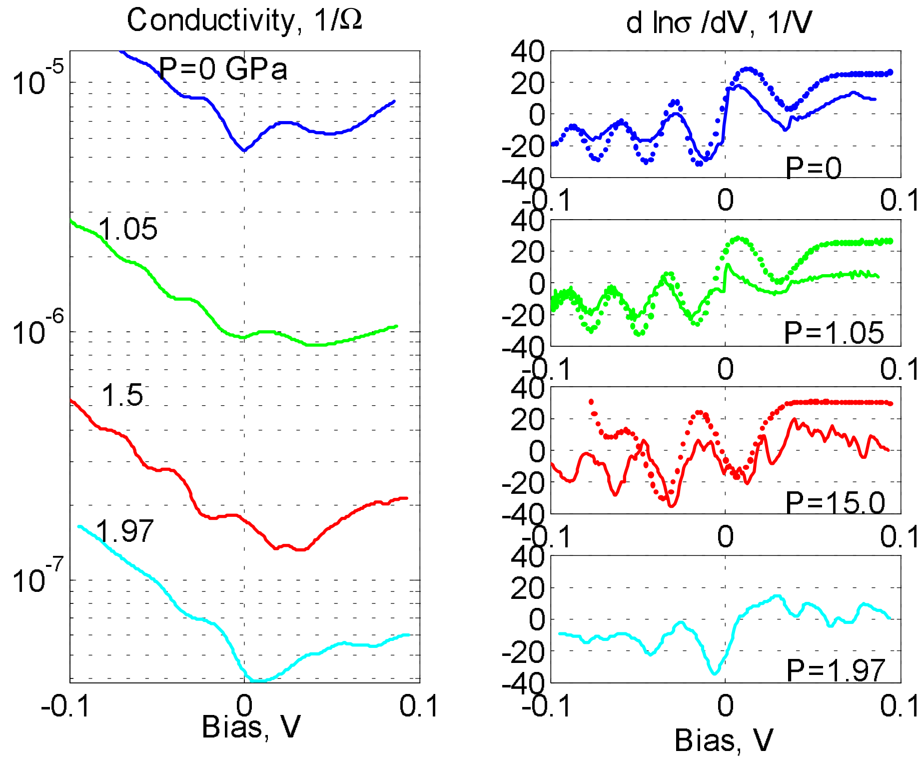

FIG. 4: Conductance σ and tunneling spectra $d\ln\sigma/dV$ at various pressures. Dotted lines correspond to model calculations.

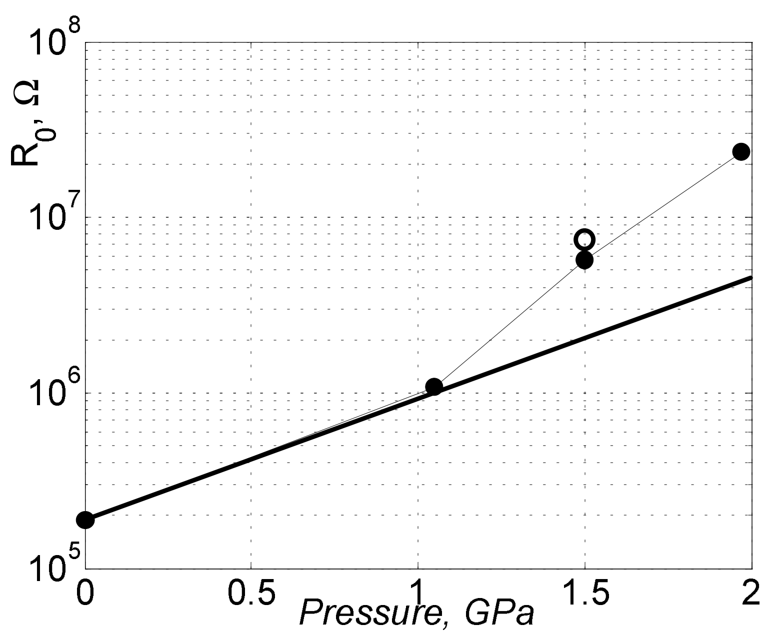

FIG. 5: Tunnel resistance at zero bias. Solid symbols are experimental data, a dashed line – theory for constant charged impurity density in the delta-layer, the open circle – theory for effective charge density $3.8 \times 10^{12}\ cm^{-2}$.